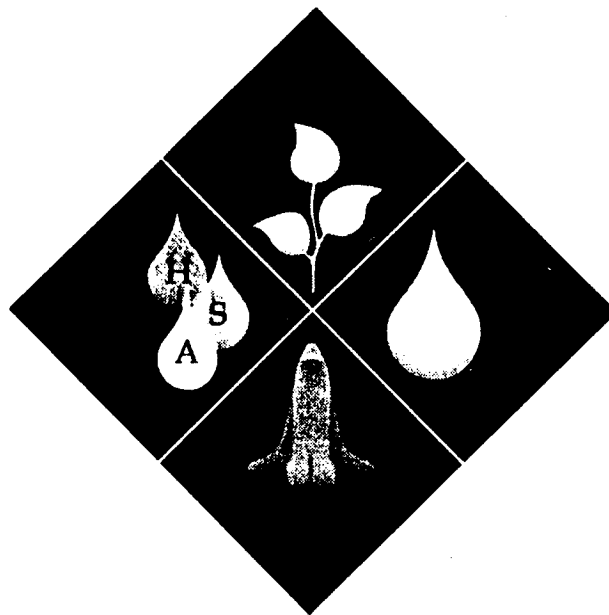Rec'd 4|14|9?

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NASA'S BIOMASS PRODUCTION CHAMBER: A TOOL FOR CONTROLLED ECOLOGICAL LIFE SUPPORT SYSTEM (CELSS) CROP STUDIES

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ABSTRACT

Over the past four years, three crops each of wheat, soybean, and lettuce have been grown in a large controlled environment chamber to study their use for life support systems in space. The chamber, called the Biomass Production Chamber, or BPC, has an atmospheric volume of 113 m^3 and provides up to 20 m^2 of growing area. To date, all plants have been grown using nutrient film technique (NFT) with lighting provided by high-pressure sodium (HPS) or metal halide (MH) lamps. The best studies with wheat have produced the equivalent of 15 g seed dry weight m^{-2} day^{-1} (using continuous lighting), while the best soybean yields averaged 6 g seed DW m^{-2} day^{-1} (with a 12-h photoperiod). The best lettuce yields averaged over 7 g head DW m^{-2} day^{-1} (16-h photoperiod), or about 185 g FW per head after 28 days. On the basis of carbon analysis of biomass, photosynthesis of the wheat stand removed about 58 g CO_2 m^{-2} day^{-1} (1.31 mol m^{-2} day^{-1}), and produced about 42 g O_2 m^{-2} day^{-1}. Both food production and gas exchange rates could be increased by increasing the photosynthetic rate with higher irradiance. Results from the BPC tests have shown the plants to be resilient and predictable in their capacity as "machines" for life support, provided the physical support systems are reliable.

INTRODUCTION

When one thinks about what it takes to keep humans alive in space, along with a suitable living habitat, some very basic requirements stand out: food, water, oxygen, and some means to handle waste products that build up (e.g. carbon dioxide). These requirements have usually been met by stowing enough supplies for the duration of the trip. Because the missions have been relatively short and close to Earth, stowage has been convenient. However, as the distance and duration of the future missions increase, so will the stowage requirements and the associated costs. Imagine traveling over a year to Mars to set up a base for scientific studies, and then still being about a year's travel time away from Earth when you are ready to return. The provisions would have to last several years, including any extra to cover mission delay or system failures. Clearly in this situation relying solely on stowage will be impractical, and recycling some of the constituents for life support would be required. These regenerative processes could be "physical-chemical" in nature, where for example the oxygen might be chemically retrieved from the carbon dioxide (Parker and West, 1973), or they could be biological, where for example plant photosynthesis is used to remove the carbon dioxide and produce oxygen and food for the humans.

Bioregenerative systems work well on Earth, and indeed it is these processes that keep the Earth's biosphere in balance and provide the food and oxygen that we need. But the Earth has enormous mass and buffers to resist rapid changes (although we humans continue to strain these systems!). In addition, the biological and ecological interactions on Earth are complex and often difficult to understand. Can such biological systems be used under the constraints of a life support habitat in space? Unlike the Earth's biosphere, life support systems for space cannot be massive (that would be too expensive), and they will have to be relatively simple to understand their operation and management.

If one considers intensive, controlled environment agriculture (CEA) as a model, where crops are grown under conditions to maintain rapid growth and high yields, the size and mass requirements of a bioregenerative life support system can be minimized. What would then be needed is a thorough understanding of the biology to manage and maintain the system. To reach this understanding, numerous questions must be addressed: For example, what crops and what cultivars are best suited for the life support habitats? Can they be grown under electric lighting and/or in hydroponics? What are the responses of the crops the different environmental factors such as temperature, lighting, CO_2, mineral nutrition, etc.?

To begin to build an information base for growing crops (higher plants) in a life support system, NASA established the Controlled Ecological Life Support System, or CELSS program (10). Over the past 10 years, CELSS has supported university studies with various candidate crops, including, wheat, soybean, lettuce, potatoes, sweet potatoes, with recent studies expanded to include cowpea, rice, oil-seed brassicas, tomatoes, carrot, and radish. (I should note that in addition to higher plants, the use of algae for bioregenerative life support systems have been studied for many years; see 5,11). The objective of these crop studies has been to define optimal environments for rapid growth and high yield, as well as selection of genotypes for controlled environments. Substantial progress has been made from these studies: For example, high yielding cultivars have been selected for many of the crops (e.g. 1,9,21), and crop responses to a range of environmental variables have been described, including lighting (1,8,21), carbon dioxide (8,27), air temperature (7,22), root temperature (16); and mineral nutrition (6,20). In addition, CELSS studies using high irradiance levels have led to extraordinary yields, often exceeding world records (2).

Despite the findings from the crop studies, tests to date have been limited in size (commonly < 1 m^2) and have not been conducted in tightly closed environments, similar to what may be expected in space. Thus a need existed to conduct tests on a large scale to address problems that would not be encountered on a laboratory or growth chamber scale. Furthermore, tests needed to be carried out in a tightly closed system to allow accurate tracking of system mass flows (e.g. CO_2 and O_2 exchange, and water and nutrient uptake), as well as characterization of any chemical or biological contaminants that might build up in a closed system.

To address these concerns, a large hypobaric test chamber at Kennedy Space Center was adapted for growing plants in a tightly closed environment. The intent of this project was to serve as a "breadboard" facility, where different plants and plant production system components could be substituted and tested. Today this chamber is referred to as the CELSS Biomass Production Chamber, or BPC (14).

CHAMBER DESCRIPTION

Descriptions of the initial design and subsystems of the BPC can be found in Prince et al. (14) and Sager et al. (17) and thus only a limited description will be given here.

The main vessel of the BPC is cylindrical in shape, measuring 3.7 m in diameter and 7.5 m high, and is currently divided into two (upper and lower) compartments (Fig. 1). Each compartment contains two plant growing levels comprised of decagonally-arranged metal shelves for supporting plant trays. Two sections of the decagonal arrangement on each level are vacant to allow access to the center of the chamber. Shelf heights are adjustable, but for all plant tests described here, the shelves were maintained at approximately 72 cm from the lamp barriers. Each level supports 16 plastic trapezoidal-shaped culture trays, with a basal (rooting) area of approximately 0.25 m^2 per tray. Thus a minimum of 4 m^2 area can be provided on each of the four levels, or a total of 16 m^2 for the entire chamber. If gaps between the trays and the tray periphery are included for canopy area, about 20 m^2 can be utilized.
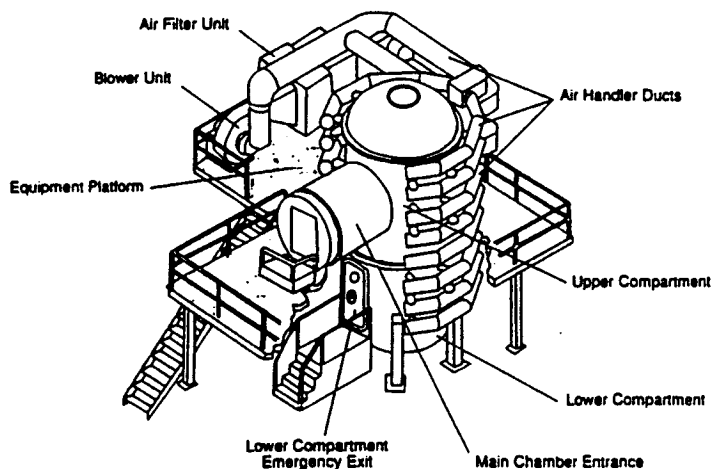

Figure 1. NASA's Controlled Ecological Life Support System (CELSS) Biomass Production Chamber.

Lighting is provided by 96, 400-W HPS or metal halide (MH) lamps separated from the plant growing area by 0.48-cm thick pyrex glass barriers. Lamps are operated with individual dimming ballasts mounted outside the chamber. Three lamps are positioned in a common bank above a set of two trays, thereby providing 1200 W input power (excluding ballast requirements) for about 0.5 m^2. With HPS lamps, a photosynthetic photon flux (PPF) of about 650 umol

m^{-2} s^{-1} can be obtained 60 cm below the barrier (80 cm below the lamps), while new MH lamps can provide about 500 umol m^{-2} s^{-1} at 60 cm. With HPS lamps, PPF levels close to 1000 umol m^{-2} s^{-1} can be reached at about 10 cm below the barrier but irradiance uniformity is poor.

Air circulation is provided by two 30-kW blowers (one for each compartment of the chamber), providing an air flow near 400 m^3 min^{-1} with velocities at the plant level of about 0.5 to 1.0 m s^{-1}. With a total internal volume of 113 m^3 (including ducting), this provides about three to four volume changes per minute. Heat rejection and moisture condensation are provided by modulating chilled and hot water flows through coil sets mounted after each blower. Following the coils, the air is filtered with a coarse, particulate filter and then a 0.3-um HEPA filter. With the exception of preliminary tests, the chamber has been operated in a closed mode, with leakage rates ranging from 5% to 10% of the volume per day (0.2% to 0.4% per hour; 17,25). During most studies, the chamber was entered once daily during the work week for maintenance activities.

Carbon dioxide (CO_2) concentrations are monitored and controlled with infrared gas analyzers, and a baseline level of 1000 ppm maintained for all the crop tests by adding CO_2 from a compressed supply to the chamber. No efforts were made to suppress CO_2 build-up from plant respiration during dark cycles (24). Oxygen concentrations are monitored continuously but not controlled. Because of periodic entrances to the chamber, O_2 concentrations were usually near 21%, i.e. close to normal ambient.

Water and nutrients were provided to the plants by continuously circulating nutrient solution through the culture trays using nutrient film technique (NFT). Solutions for each of the levels were held in separate PVC tanks located outside the chamber, with the head space of each tank vented back to the main chamber. Each tank has a maximum capacity of 300 L, although most tests were conducted with about 180 L of solution in each tank. In addition, a volume of 30 to 50 L of solution was contained by the trays and plumbing for each level. For all the tests reported, a 1/2 strength, Hoagland-type nutrient solution was used, with minor adjustments made depending on the crop. Solution pH was controlled automatically at 5.8 to 6.0 by additions of dilute nitric acid, and except for the very earliest studies, solution

electrical conductivities were controlled automatically to 0.12 S m^{-1} with additions of a concentrated stock solution. Tank volumes were maintained by adding deionized water each day. Flow rates to individual trays typically averaged 0.5 to 1.0 L min^{-1}.

For all tests, plant seeds were sown directly between strips of white-on-black polyethylene plastic supported by rigid tray inserts (Fig. 2; see 15). This system supported germinating seeds about 1 to 2 cm above the bottom of the tray, while allowing roots to grow between the strips to reach the flowing nutrient solution. The tensioned strips also maintained darkness in the root zone, thereby minimizing any algae growth. Nylon fabric wicks were placed in each gap between the strips to maintain capillary contact with the nutrient solution.
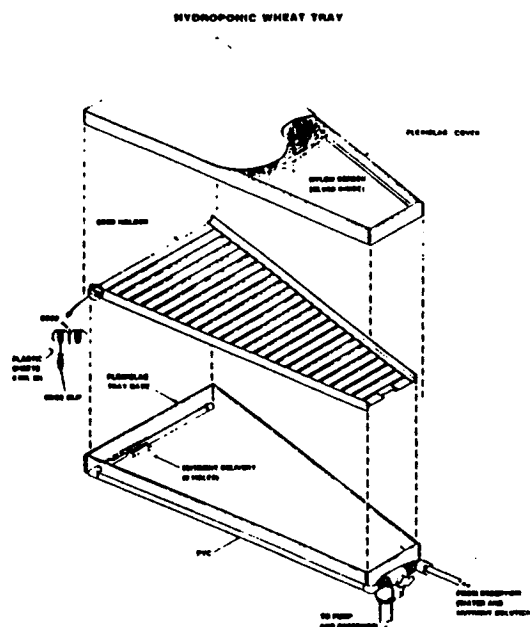

Figure 2. Schematic of hydroponic (NFT) culture tray used to grow crops in the Biomass Production Chamber. The upper plexiglas cover was removed after seeds had germinated.

CROP STUDIES IN THE BPC

Wheat. The upper two levels of the chamber were operational by May 1988 and a crop of wheat (*Triticum aestivum* L. cv. Yecora Rojo) was planted in the upper compartment of the chamber (32 trays, 16 per shelf). Plants were grown using continuous light (i.e.

Table 1. Photosynthetic photon flux (irradiance) levels for crop tests in NASA's Biomass Production Chamber.

Crop	Date	Average[1] PPF (μmol m^{-2} s^{-1})	Photoperiod (hrs)	Daily PPF (mol m^{-2} day^{-1})	Length of Study (days)
Wheat	5-88	666	24	57.5	68-86
Wheat	1-89	535	20	38.5	86
Wheat	5-89	691	20	49.7	85
Soybean	11-89	815	12	35.2	90
Soybean	5-90	477	12	20.6	97
Soybean	11-90	644	10	23.2	97
Lettuce	3-90	290	16	16.7	16-28
Lettuce	9-90	280	16	16.1	28
Lettuce	9-91	293	16	16.9	16-28

[1] PPF = photosynthetic photon flux

a 24-hr photoperiod) with HPS lamps, with an average of 666 umol m^{-2} s^{-1} PPF at the top of the plant canopy (Table 1). Temperatures were maintained at 23°C throughout growth and plants were harvested at 68, 74, 80, and 86 days after planting. In February 1989, all four levels of the chamber (64 trays) were planted with 'Yecora Rojo' wheat and plants were harvested after 86 days. Lighting was again provided by HPS lamps but with a 20-hr photoperiod and lamps were dimmed beginning at 28 days after planting to maintain approximately 500 umol m^{-2} s^{-1} PPF at the plant canopy (Table 1). Temperatures were maintained at a constant 23°C and then switched to 20°C in the light and 16°C in the dark on day 35. A third full-term growout with wheat was started in May 1989, again with a 20-hr photoperiod but with no dimming of the HPS lamps, providing an average of 691 umol m^{-2} s^{-1} at the canopy level. Temperatures were held at 23°C and then switched to 20°C in the light and 16°C in the dark at day 14. Plants for the third test were harvested 85 days after planting. For all wheat tests, seeds were sown at a rate of approximately 1600 m^{-2}, and carbon dioxide (CO_2) concentrations were maintained at 1000 ppm during the light period.

Soybean. In November 1989, soybeans (Glycine max (L) Merr. cv McCall) were planted to provide six plants per tray, or 24 plants m^{-2}. Lighting was provided with HPS lamps with a 12-hr photoperiod, with canopy-level PPF averaging about 815 umol m^{-2} s^{-1} (the canopy-level PPF average was higher than that of wheat because the soybean plants grew taller and hence closer to the lamp barrier; Table 1). Temperatures were maintained at 26°C in the light and 20°C in the dark. As with wheat, CO_2 level was maintained at 1000 ppm in the light. Plants were harvested at 90 days after planting. A second crop of soybeans was planted in May 1990, using metal halide (MH) lamps to provide a broader spectrum of radiation. Photoperiod, temperature and [CO_2] were as before. Canopy-level PPF averaged 477 umol m^{-2} s^{-1} (Table 1), and plants were harvested at 97 days. A third test with soybean was planted in November 1990, but this time with HPS lamps in the upper two levels and MH lamps on the lower two levels. In addition, the photoperiod was reduced to 10 hr light and 14 hr dark. Temperature was again 26°C in the light and 20°C in the dark, [CO_2] was maintained at 1000 ppm in the light, and plants were harvested at 97 days.

Lettuce. In April 1990, lettuce (Lactuca sativa L. cv. Waldmann's Green) was planted to provide six plants per tray, or 24 plants m^{-2}. Lighting from HPS lamps was dimmed to maintain 300 umol m^{-2} s^{-1} PPF at the canopy level with a 16-hr photoperiod (Table 1); temperature was maintained at 23°C and CO_2 at 1000 ppm during the light period. Plants were sequentially harvested at 16, 18, 20, 22, 24, 26, and 28 days after

planting. A second lettuce test was planted in September 1990, using MH lamps and only a single harvest at 28 days. As with the first study, PPF was maintained at 300 umol m^{-2}s^{-1}, a 16-hr photoperiod, a constant 23°C, and 1000 ppm CO$_2$ during the light. A third lettuce study was conducted in September 1991 again using HPS lamps with sequential harvests at 16, 18, 20, 22, 24, 26, and 28 days. Except for controlling the nutrient solution temperature to 26°C, other conditions were similar to the previous lettuce studies.

CROP YIELDS

Harvest data from the studies with wheat, soybean, and lettuce are shown in Table 2. Data represent the average oven-dry weights for all the trays in the chamber expressed per unit area (kg m^{-2}), as well as yield per unit area, per unit time (g m^{-2} day^{-1}). For all calculations, stand area was assumed to be 16 m^2. Results showed that the highest wheat yield was obtained from the trial using continuous light – 1.2 kg seed DW m^{-2}, or approximately 15 g seed DW m^{-2} day^{-1} (Table 2). Total biomass averaged about 2.9 kg m^{-2}, or 37 g m^{-2} day^{-1}. If one looks only at the four best trays from this study (i.e., a 1-m^2 subsample), yields averaged 1.6 kg seed m^{-2}, or about 22 g m^{-2} day^{-1}, while total biomass averaged

3.6 kg m^{-2}, or about 50 g m^{-2} day^{-1} (data not shown). This suggests yields from the chamber as a whole can be increased. By comparing the yields between the three wheat studies, a correlation is apparent between total radiation provided and total biomass produced (Tables 1 and 2), indicating that further increases in yield should be attainable with increased irradiance [1].

Soybean seed yields were nearly equal for both the first study using a 12-hr photoperiod with HPS lighting and the third study using a 10-hr photoperiod with HPS lighting – 0.5 kg seed DW m^{-2} (Table 2). However, total biomass was highest from the first study using 12 hrs of HPS lighting – 1.7 kg m^{-2}, again indicating that total light provided to the plants was a strong influence. The fact that seed yields from the 10-hr and 12-hr photoperiod were nearly equal despite the 12-hr plants receiving more total light (Table 1), indicates that plants under the shorter photoperiod partitioned more energy to seed growth (i.e. a higher harvest index). Although cv. McCall is considered relative day-neutral for flowering in the field, the harvest index values suggest that a "short-day" tendency still exists. In addition, a comparison of HPS and MH lamp treatments between the first and second study (Table 2), and within the third study (data not shown), suggests that broader

Table 2. Yields (dry matter) of crops grown in NASA's Biomass Production Chamber.

Crop	Date	Edible Yield[1]		Total Biomass	
		(kg m^{-2})	(g m^{-2} day^{-1})	(kg m^{-2})	(g m-2 day^{-1})
Wheat	5-88	1.16	15.0	2.88	37.4
Wheat	1-89	0.67	8.0	2.36	27.4
Wheat	5-89	0.82	9.6	2.76	32.5
Soybean	11-89	0.54	6.0	1.66	18.5
Soybean	5-90	0.40	4.1	1.18	12.2
Soybean	11-90	0.49	5.0	1.30	13.4
Lettuce	3-90	0.16	5.7	0.17	6.0
Lettuce	9-90	0.16	5.8	0.18	6.3
Lettuce	9-91	0.20	7.2	0.22	7.9

[1] Assumes planted area = 16 m².

spectrum irradiance also favors partitioning to seeds and high harvest index in soybean, although the difference PPF levels between the lamp treatments make direct comparisons difficult.

The highest edible yields from lettuce were obtained from the third test, using HPS lamps and a double-wick seedling establishment system – 0.20 kg DW m^{-2}, or 7.2 g m^{-2} day^{-1} (or about 185 g head FW per plant in 28 days). Yields from the second test using metal halide lamps were slightly less, 0.16 kg DW m^{-2}, or 5.8 g m^{-2} day^{-1}. The lower productivity from the first study in comparison to the third study, which also used HPS lamps, likely reflects the influence of adding a double-wick establishment system. The generally low productivity (g m^{-2} day^{-1}) of lettuce in comparison to other crops is a result of the lower irradiance used for the tests and the proportionately greater time to achieve canopy cover. (Note, the lettuce plants were harvested soon after reaching complete canopy closure). If an automated spacing systems were incorporated to spread plants out with age (13), the total area requirement would have been reduced and production per unit area per unit time would have increased.

CO_2/O_2 EXCHANGE

Analyses of wheat biomass showed that the tissue averaged about 42% carbon (4; and T.W. Dreschel unpublished). With the exception of the initial planted seed, the carbon in the harvested biomass came from CO_2 fixed during photosynthesis. Thus for the first wheat study, (37.4 g biomass m^{-2} day^{-1}) x (0.42 carbon), or 16 g carbon m^{-2} day^{-1} were fixed. This would equate to 58 g, or 1.31 mol CO_2 m^{-2} day^{-1} (Table 3). If we assume for wheat that most of this was fixed as carbohydrate, then approximately 1.31 mol O2 m^{-2} day^{-1} (i.e., a 1:1 ratio of O_2 produced to CO_2 fixed), or 42 g O_2 m^{-2} day^{-1} would be produced (Table 3). Further discussion of direct measurements of crop gas exchange can be found in Wheeler and Sager (24).

IMPLICATIONS FOR HUMAN LIFE SUPPORT

Food Requirements. Using the best yields obtained from the BPC, one can estimate the total area of plants required to sustain one person: Assuming a dietary requirement of 2500 kcal day^{-1}, an energy content of 3.7 kcal g^{-1} DW of wheat seed, and a productivity of 15 g seed DW m^{-2} day^{-1} (Table 2), then an area of 45 m^2 in continuous production

would be sufficient to sustain one person (Table 3). This is approximately 7 m by 7 m, or two to three times the current planted area in the BPC. Using a similar calculation for the yields from the best four trays (22 g m^{-2} day^{-1}) indicate that an area of only 30 m^2 per person should be possible, which is similar to estimates obtained with other crops (21). It is also important to note that these calculations only apply to the seed yield. Thus, if some of the inedible biomass (i.e. straw, chaff and roots) could be converted to food, e.g. through enzymatic conversion of cellulose to simpler carbohydrates (19), the effective productivity of food would be increased and the required area decreased even further.

Short-term tests of stand photosynthetic rates indicate that factors such as $[CO_2]$, temperature, and humidity can be maintained close to optimal levels for plant growth (24), thus further improvements in yield will likely come from improved cultural techniques, better adapted cultivars, and increased lighting. Bugbee and Salisbury (2) reported wheat yields up to 60 g m^{-2} day^{-1} seed DW with an irradiance of 150 mol PAR m^{-2} day^{-1}, indicating that area requirements with wheat could be reduced even further with increased irradiance. Whether other crops with more horizontal leaf architectures and/or short-day tendencies can sustain increased production with increased irradiance remains to be tested. Recent findings from potato studies indicate that productivities may saturate at irradiance levels well below those shown for wheat (27). Ultimately, the availability and cost of energy to provide lighting versus the cost of increased growing area will dictate the most favorable approach.

Water Requirements. Water condensed from the air handling system during the first wheat study averaged about 5.9 L m^{-2} day^{-1} (Table 3). If a total water requirement (including wash-water, etc.) is assumed to be 17.5 L person^{-1} day^{-1}, then about 3 m^2 of wheat would be required per person (Table 3). The subsequent studies with wheat and soybeans resulted in stand transpiration rates near 5 L m^{-2} day^{-1} (data not shown), hence it appears that a relatively small area of plants could be used to regenerate water for humans. It is important to note, that an equal amount of water must be provided to the roots to sustain this transpiration, but in theory this could be "gray" water with the appropriate nutrient balance. Further testing is required to determine whether optimal crop yields can be sustained using this approach.

Table 3. Human equivalents supported by a wheat crop grown in NASA's Biomass Production Chamber. Photosynthetically active radiation equaled 57 mol m^{-2} day^{-1}.

	BPC Rate (g m^{-2} day^{-1})	Human Requirement (g day^{-1})	Area Required for One Person (m^2)
Food (from seed)	15	675[1]	45
Food (seed from 4 best trays)[2]	22	675[1]	30
CO_2 Removed	58[3]	1000[4]	17
O_2 Produced	42[3]	850[4]	20
H_2O Produced	5900	17,500[5]	3

[1] Assumes 2500 kcal person-1 day-1 and 3.7 kcal g-1 DW of food

[2] Assumes yield from four best trays could be obtained consistently.

[3] Estimated by calculating amount of CO2 required to produce biomass with 42% carbon. Oxygen produced was assumed to be at 1:1 molar ratio with CO2 removed.

[4] Rates at rest or very light activity (Parker and West, 1973).

[5] Estimate of total water needs per person, including drinking, food preparation, washing, etc.

Gas Exchange Requirements. Results from the best wheat study indicate that the plant stand would remove an average of 58 g of CO_2 m^{-2} day^{-1} (Table 3). Assuming and output of 1000 g CO_2 per person day^{-1}, then about 17 m^2 of wheat under these environmental conditions would be required to remove the CO_2 from one person. The same stand would produce about 42 g O_2 per day, indicating that 20 m^2 would be required to provide enough O_2 for one person (Table 3). Note that the molar ratio of CO_2 produced to O_2 consumed is not 1:1 for humans, reflecting the influence of fat metabolism in human respiration (12). This creates some potential imbalances with regard to plant photosynthesis, which can be closer to a 1:1 ratio of CO_2 removed to O_2 produced, especially for carbohydrate producing plants (5). As with food (biomass) production, anything that would increase photosynthesis, e.g. higher irradiance, would likewise increase CO_2 removed and O_2 produced and reduce the area required per person.

The estimates of required plant area for CO_2/O_2 exchange shown above are based on the assumption that only the carbon in the food (i.e. edible biomass) will be recycled back to CO_2 through human respiration. Such a scenario could be envisioned in a system where a portion of food is imported to supplement any food produced on-site, and then any inedible biomass is considered waste and not recycled. In this case, the plants would serve primarily for O_2 production and CO_2 removal. A more likely scenario, however, might involve total carbon recycling to minimize import costs. In the simplest case, the inedible biomass could be oxidized (e.g. combusted) back to CO_2, H_2O, and its inorganic constituents for recycling. In this case, the initial gas exchange rates must then be adjusted for the amount of inedible biomass that is burned, since this will consume O_2 and release CO_2. For the wheat data shown in Table 3, the net production rates would be decreased by about 60%. Thus in a carbon-recycling life support system, the production of food obtained from the plant biomass profoundly affects the balance of CO_2 and O_2. Anything that increases the return of food, e.g. higher harvest index, or the conversion of a portion of the inedible biomass to food, would result in reduced area for CO_2 removal and O_2 production. Ultimately, if sufficient food is produced, then sufficient CO_2 removal and O_2 production would follow, since any excess biomass beyond food requirements can be oxidized and recycled without jeopardizing the gas exchange requirements.

COMMENTS ON THE PERFORMANCE OF THE BPC

Plant Culture. The crops tested to date in the BPC have all performed well with nutrient film culture (NFT), and harvesting and tray clean-up have been relatively easy. In addition, recent tests with sweet potatoes and potatoes showed that storage roots and tubers develop well in NFT (9, 23), indicating that NFT is a good compromise for a variety of crops. Whether it is optimal for any individual crop, especially under high irradiance, remains to be tested (see 3). One obvious hazard to NFT with a minimal volume of water in the root zone is the risk of desiccation during a pump or plumbing failure; thus alarms for water flow in the nutrient delivery system are essential.

Despite preliminary growth chamber studies, the vertical constraints of the BPC (approx. 60 cm per level) created some problems. With soybeans, the shoots reached to lamp barriers resulting in poor air circulation at the top of the canopy. The blue deficient spectrum of the HPS lamps could have contributed to this (26), as could the choice of temperatures, solution nitrogen concentration, plant spacing, and other factors. Wider spacing likely would reduce the tendency for tall growth but would result in reduced total light interception early in stand development. Reduction in temperature might also be used, but at the risk slowing overall plant growth; a similar risk of reducing growth may exist if nitrogen is reduced, although further studies with nitrogen could be informative. Perhaps a more effective approach would be continued screening of cultivars for short canopy height (e.g. dwarfs). Of course, these constraints are somewhat particular to the BPC, yet short canopy stature would always seem to be desirable trait for a CELSS crop.

Chamber Operation. To date, the BPC has operated for over 700 days (17,000 hrs) and has proven to be an invaluable tool for CELSS research. BPC tests have served as the only source of large system mass balance (e.g. CO_2, O_2, and H_2O exchange rates) and biomass productivity data for the program. In addition, the tight closure of the chamber has allowed tracking of ethylene and other volatile contaminants (B. Vieux and S. Mosakowski, unpublished), and the description of solution and atmospheric microflora (18); to date, these are unique plant research data sets.

Although the yields from some studies have been less than estimates from laboratory or growth chamber tests, areas for improvement on a systems level are becoming apparent; until now, such discussions were largely speculative. It is noteworthy that throughout the testing of crops in the BPC, the plants as biological "machines" for a life support system have been resilient and predictable: Invariably, anomalies in gas exchange and/or productivity of the crops could be traced to a physical system event or failure, e.g., power outage, pump failure, etc. Although further testing is needed, particularly with long-duration crop cycles, the reliability of the plants is a critical observation.

Improvements can, and should be made for future testing with crops for bioregenerative life support systems, and the BPC should continue to serve as a useful tool for many years. Plans are in place to link the biomass (plant) production area to resource recovery (waste treatment) and food preparation modules to generate systems-level data for a more thorough assessment of the CELSS concept.

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